Cosmic Ray Antiproton Observations by the Isotope Matter-Antimatter Experiment; 0.2 to 3.2 GeV

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Abstract

We have positively identified sixteen mass-resolved cosmic ray antiprotons with energies between 0.2 and 3.2 GeV using the IMAX balloon-borne magnetic spectrometer. Mass was determined by velocity vs. magnetic rigidity techniques using a high resolution time-of-flight system and silica-aerogel Cherenkov detectors. The antiprotons are clearly separated from the low-mass particle background. Here the measurement technique, data analysis, and resulting proton and antiproton mass histograms are presented.

1. INTRODUCTION

The Isotope Matter-Antimatter Experiment (IMAX) was designed to measure cosmic ray antiprotons and light isotopes over an energy range from 0.2 GeV/nucleon to over 3 GeV/nucleon as well as to search for antihelium and to measure muon spectra. The IMAX results in other areas are given elsewhere in these proceedings (Reimer *et al.*; Davis *et al.*; Krizmanic *et al.*). The interpretations of the results presented here are discussed in a following paper (Labrador *et al.*) in these proceedings.

Antiprotons are commonly produced in high energy nuclear collisions and thus are expected as secondary products of interactions between the primary cosmic radiation and the interstellar medium. As detected at Earth, the secondary antiproton flux reflects the kinematics of antiproton production as well as the effects of solar modulation. Early measurements ([1], [2], [3]) spanning the range from 0.1 to 10 GeV showed various degrees of apparent excess when compared to standard models of secondary antiproton production and transport. Various explanations were proposed including an extragalactic component, matter-shrouded cosmic ray sources, production in relativistic plasmas, and the decay of primordial black holes.

The results of PBAR [4] and LEAP ([5], [6]) showed that there was probably no appreciable antiproton excess below 1 GeV. This has been confirmed by BESS [7]. However, unlike IMAX, none of these experiments were capable of measuring the antiproton flux over the full leading edge of the (solar modulated) antiproton production spectrum.

2. INSTRUMENT DESCRIPTION

IMAX identifies antiprotons based on charge and mass using measurements of magnetic rigidity, ionization energy loss, and velocity. IMAX has been described in detail elsewhere [8] and we only note its most important features.

IMAX employed drift chambers (DC) and MWPCs located in the high field region of a (61 cm diameter) single-coil superconducting magnet. The magnet and MWPCs are described in [9] and [10]. The eight MWPCs, with upgraded readout to record multiple hits in the lower chambers, gave eight measurements in the bending direction and four in the nonbending direction. The DC system consisted of two chambers, each containing ten layers (six giving positions in the bending direction) of hexagonal drift cells [11] with an average position resolution of about 100 μm. The characteristic maximum detectable rigidity (MDR) for the hybrid tracking system was 200 GV/c for Z=1 particles.

Particle velocities were obtained from a time-of-flight (TOF) system [12], and two silica-aerogel Cherenkov counters (C2 and C3) [13]. The TOF scintillators and two additional light-integrating scintillators (S1 and S2) gave four independent measurements of particle charge. The TOF resolution was 122 ps for $Z=1$, $\beta=1$ particles over a flight path of 2.5 m. For $Z=1$, $\beta=1$ particles, C2 and C3 yielded 11 and 13 photoelectrons respectively from 9 cm each of n=1.043 silica aerogel. The average total PMT noise from C2+C3 was much less than one photoelectron.

The IMAX flight took place on July 16-17, 1992, from Lynn Lake, Manitoba, Canada. Float duration was 16 hours at an average altitude of 36 km.

3. DATA QUALITY REQUIREMENTS

Singly charged particles were selected using a four-fold consistency between charges derived from (mapped) signal amplitude vs $1/\beta$ (TOF) in the two TOF layers, S1, and S2. A number of data quality requirements were imposed, independent of charge sign.

The quality of the fitted particle trajectory through the spectrometer is of particular importance in the antiproton measurements since it is possible for scattering to give a measured curvature which is quite different, even in sign, from the actual track. As a result, we require that the final fitted track utilize at least 11 position measurements in the bending direction and 7 in the nonbending direction. In addition, the fit in each direction must have a reduced $\chi^2 \leq 4$. To negate the effects of multiple tracks, neither set of position measurements can have more than 3 drift chamber layers with a hit over 4 cm off the fitted track. The rigidity resolution of the track, related both to fit quality and to the integral field traversed, must be better than 50 GV/c. To eliminate hard scattering events, the rigidities obtained from the top DC, the bottom DC, and the full tracking system must be in agreement. The tracks of all antiproton candidates are also individually examined for evidence of hard scatters which the calculated cuts may not have eliminated. No candidates had to be eliminated as a result. As a final tracking check and to further reduce any contamination from multiple tracks, the position along the TOF paddles derived from timing and the projected position of the fitted trajectory must agree to better than 5 cm.

To insure consistent velocity and charge measurements, the fitted track must pass through the active areas of all detectors, leading to an effective geometry factor of 144 cm^2sr. Cherenkov PMTs must have individual amplitudes of less than 5 photoelectrons since an anomalously large signal may indicate that a particle passed through the photocathode. The signals in the two Cherenkov counters must be correlated to within photo-statistical fluctuations. Finally, the velocity derived from the TOF and from the Cherenkov detectors must agree within the respective uncertainties of the two systems.

4. ANTIPROTON MEASUREMENTS

For proton kinetic energies between 0.2 and 2.6 GeV, mass is determined by β (TOF) vs. magnetic rigidity. To enhance discrimination against the low-mass background, we require that no significant signal be detected in C2 and C3. Both C2 and C3 are mapped carefully and the signals are normalized so that the total C2+C3 signal expected from a $\beta=1$, $Z=1$ particle is equal to. The TOF energy range protons and antiprotons were required to have a normalized C2+C3 signal of less than 0.16. This introduces a small detection inefficiency due to the production of fast δ-rays. The resulting mass separation is shown in Figure 1 in which the TOF velocity is plotted vs. rigidity. Antiprotons (stars), protons, deuterium, and tritium are clearly visible and are well separated from the low-mass particles.

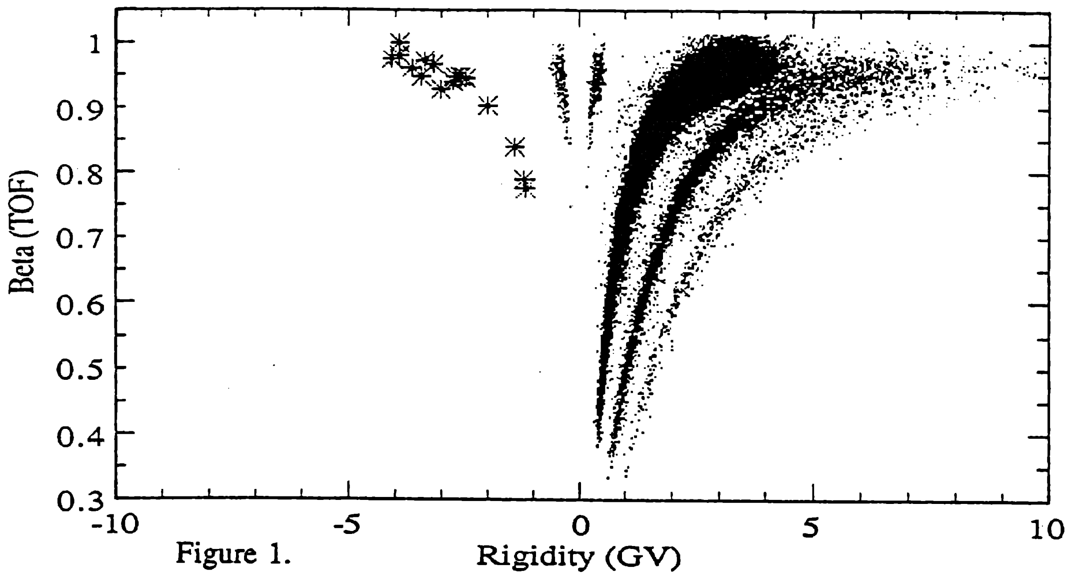

Figure 1.

From 2.6 to 3.2 GeV, mass is determined by β (Cherenkov) vs. rigidity. This energy range, corresponding to normalized C2+C3 signals between 0.16 and 0.36, was chosen to give good mass resolution and to avoid contamination both from δ-ray production and from downward fluctuations of the Cherenkov signals of fast low-mass particles. The mass separation obtained using the Cherenkov detectors is shown in Figure 2 in which the square root of the absolute value of the normalized C2+C3 signal is plotted vs. deflection (1/rigidity). Low-mass particles occupy the nearly horizontal band. Protons, deuterium, and tritium are visible at positive deflections. From 2.6 to 3.2 GeV (ordinates from 0.4 to 0.6) the antiprotons (stars) are well separated from background.

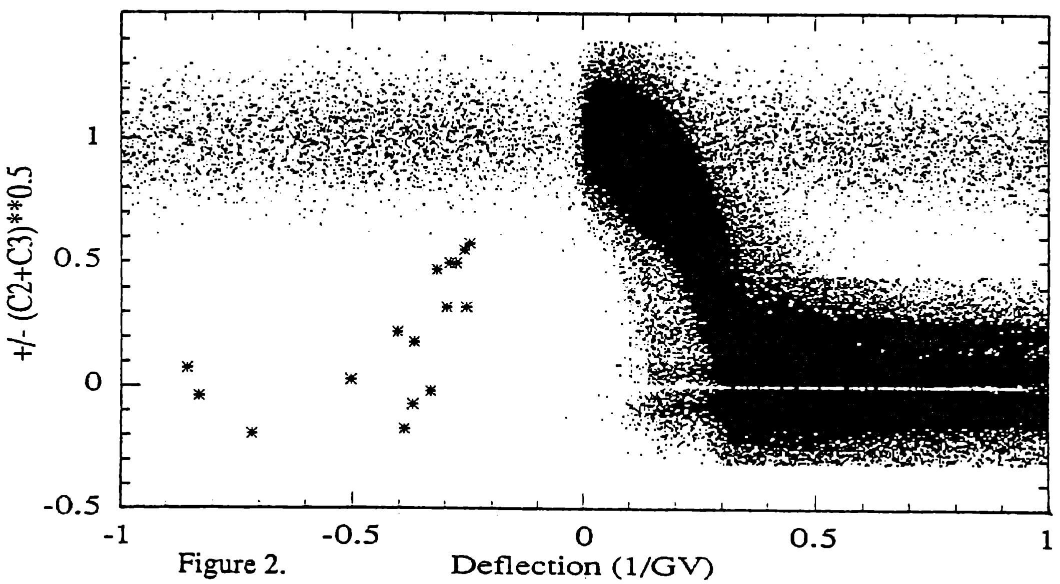

Figure 2.

We have broken the TOF energy range into two separate bins: 0.2 - 1 GeV, and 1 - 2.6 GeV, while the Cherenkov energy range (2.6 - 3.2 GeV) is reported in a single bin. The mass histograms for these bins, in Figure 3, show the protons and antiprotons to be well resolved and very clearly separated from the low-mass components. Three antiprotons were identified in the lowest bin, eight in the middle bin, and five in the highest bin.

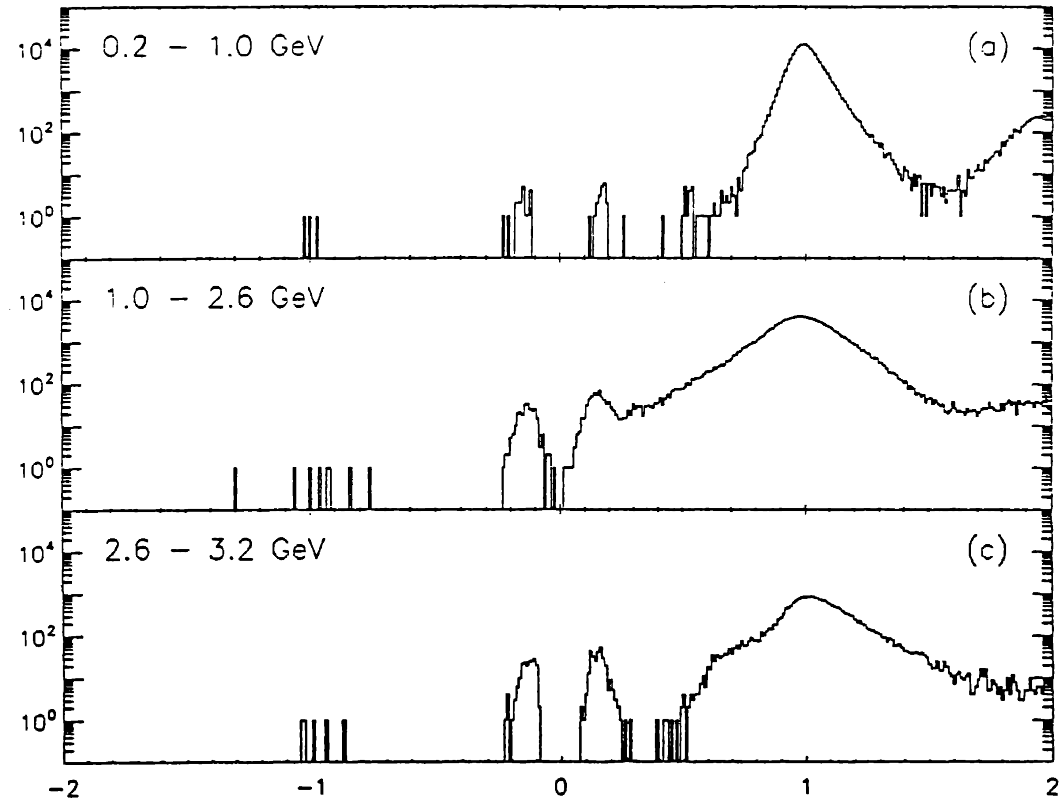

Figure 3.

5. CONCLUSIONS

IMAX has proven highly successful in achieving its design goals and has shown excellent mass resolution and background rejection over a wide energy range. We have positively identified sixteen antiprotons with energies between 0.2 and 3.2 GeV. All of the antiprotons are clearly mass resolved and separate from background. IMAX has successfully measured the antiproton population over the full energy range where the leading edge of the secondary antiproton spectrum is expected.

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REFERENCES

[1] Golden, R.L. *et al.*, Phys. Rev. Lett. **43** (1979) 1196.
[2] Bogomolov, E.A. *et al.*, Proc. 16th ICRC **1** (1979) 330.
[3] Buffington, A. et al., Ap. J. **248** (1981) 1179.
[4] Ahlen, S.P. et al., Phys. Rev. Lett. **61** (1988) 145.
[5] Stochaj, S.J., Thesis - Univ. of Md. (1990) unpublished.
[6] Streitmatter, R.E. *et al.*, Adv. Sp. Res. **9** (1989) 1265.
[7] Yoshimura, K. *et al.*, Phys. Rev. Lett. (1995) submitted.
[8] Mitchell, J.W. *et al.*, Proc 23rd. ICRC **1** (1993) 519.
[9] Golden, R.L. *et al.*, Nucl. Inst. and Meth. **148** (1978) 179.
[10] Golden, R.L., *et al*, Nucl. Inst. and Meth. **A206** (1991) 366.
[11] Hof, M. *et al.*, Nucl. Inst. and Meth. **A345** (1994) 561.
[12] Mitchell, J.W. *et al.*, Proc 23rd. ICRC **2** (1993) 627.
[13] Labrador, A.W. *et al.*, Proc. 23rd. ICRC **2** (1993) 524.